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# CORRELATIONS BETWEEN DEM-DERIVED TOPOGRAPHIC INDICES AND REMOTELY-SENSED VEGETATION COVER IN RANGELANDS

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## ABSTRACT

The paper describes an attempt to relate patterns of vegetation cover with topography and a set of biological and grazing intensity variables in a mountain and piedmont area of arid central Australia. Vegetation cover, as measured by an index based on data from the Landsat satellite, can also be used as an erosion/deposition surrogate so the results have implications for distributed erosion models. A simple, analytically based erosion model derived from the continuity equation does not reproduce observed patterns of vegetation cover, and neither do various topographically based moisture indices. A regression approach shows that patterns of vegetation cover are related to topography but the most important predictors are biological ones, with percentage of bare ground upslope being the strongest. Tests with variable drainage area show that relationships between cover and topography, bare area upslope and grazing effects change systematically with basin size and that scale effects are present. Distributed erosion models are not yet capable of handling biological processes very well, yet these processes must be incorporated if erosion prediction is to be successful.

KEY WORDS vegetation cover; topography; erosion; moisture indices; distributed models; rangelands; remote sensing

## INTRODUCTION

Vegetation cover in arid and semi-arid rangelands is a major determinant of sediment availability, erosion rate and runoff (e.g. Hoffman *et al.*, 1983; Johns, 1983; Eldridge and Rothon, 1992). Indeed, the close link between plant cover and soil moisture and erosion status makes it attractive to use vegetation cover as an indicator of surficial hydrologic and erosion processes, given that cover can be measured with relative ease from remotely sensed data. A number of authors have therefore advocated or successfully used vegetation indices or spectral variables derived by remote sensing to infer erosion status (e.g. Frank, 1984; Warren and Hutchinson, 1984; Pickup and Nelson, 1984; Graetz *et al.*, 1986; Hill *et al.*, 1993).

The ability to measure vegetation cover from satellites on a regional basis has come at a time when spatially distributed models of hydrologic processes and of erosion and deposition are increasingly prominent in the literature (e.g. Kirkby, 1971; Smith and Bretherton, 1972; Dietrich *et al.*, 1993; Moore *et al.*, 1991; O'Loughlin, 1986). These models rely heavily on topographic indices, such as drainage area, slope and hillslope curvature, when making predictions. Given the close relationship between vegetation cover, hydrologic process and erosion status, there should also be linkages between the topographic indices and vegetation cover.

In this paper we examine the effect of topography on vegetation cover on the mountain ranges, alluvial fans and footslopes of drainage basins in arid central Australia. Our approach is to use the topographic indices commonly employed in distributed hydrologic and erosion models as indicators of moisture redistribution and soil loss or accumulation in the landscape. The spatial patterns shown by these indices are compared with the observed distribution of vegetation cover obtained from satellite imagery. The

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topographic indices were obtained using digital elevation models (DEMs) derived from topographic maps with a 20 m contour interval. While this may be too coarse for accurate prediction, it is all that is likely to be routinely available in many areas. Obviously we do not expect the indices to predict cover directly since other variables may be involved, but there should be some correspondence between general patterns.

The area chosen for the study is a difficult one to deal with because the terrain includes steep mountain slopes with bare rock or a coarse talus mantle, alluvial fans and footslopes with a mix of fine and coarse material, and extensive plains with fine-grained alluvial or aeolian soils. There is also an important biological element in both the pattern of vegetation cover and the distribution of soil moisture, runoff, erosion and deposition because the spatial distribution of cover is closely related to the spatial pattern of grazing (e.g. Pickup and Chewings, 1988a). Spatially variable grazing has never been built into a distributed runoff or erosion model, although Thornes (1990) and Biot (1993) have considered grazing as a point process. It is therefore useful to see the extent to which vegetation cover reflects grazing impact as well as topographic variation.

## BACKGROUND

### *Factors affecting distribution of plant cover*

Vegetation growth in arid areas is moisture-limited but is also influenced by soil type, nutrient availability and the extent of grazing. Moisture availability is a function of rainfall and evaporation. It also varies spatially due to redistribution by runoff and runon, both of which are a function of topography (Stafford Smith and Pickup, 1993). Soil type and nutrient availability also vary spatially, and it is common to find that depositional areas provide an environment more conducive to plant growth than eroding or stable areas in the landscape (e.g. Friedel *et al.*, 1993).

While vegetation cover is closely linked with hydrologic and erosion processes, the relationship does not remain constant through time. This is because vegetation behaviour in arid areas consists of a series of rainfall-generated pulses or growth periods during which biomass builds up as production and reproduction occur (e.g. Noy-Meir, 1973; Westoby, 1980; Friedel, 1984). After the growth period, moisture becomes limiting once more and plant activity is reduced. Much of the biomass produced during the growth period is then lost through plant mortality, consumption by grazers, conversion to litter and biological decay.

The rate of cover loss after a growth pulse largely depends on the amount of grazing and the rate of natural decay. Natural decay rates vary with season and with plant species composition, but should not vary systematically in space within a particular landscape type. Grazing intensity does vary across the landscape and shows a pattern governed primarily by distance from water, forage availability and animal preferences for particular forage types (e.g. Hodder and Low, 1978). Of these, distance from water provides the strongest pattern in the landscape, although its effect may be rendered complex by the effects of topography (Pickup and Chewings, 1994).

The effects of short-term variability in vegetation cover can be removed by averaging over a period of time. The resultant pattern is then more closely related to the likely distribution of runoff and erosion and deposition, because average cover levels incorporate the effects of grazing as well as the amount of time the soil remains unprotected by plants.

Grazing produces two major spatial patterns at the regional scale: grazing gradients and intensified natural patterns of erosion and runoff redistribution (Pickup and Chewings, 1994). Grazing gradients are radial or star-shaped patterns of plant cover change or erosion and deposition centred on natural or artificial waters. They develop because grazing animals must return to these locations at regular intervals to drink (Pickup and Chewings, 1988a). Natural erosion and runoff redistribution patterns which can be intensified by grazing fall into two basic types. In the flatter areas, patterns of active erosion and deposition are dominated by erosion cell mosaics (Pickup, 1985). In steeper areas, where there are tributary drainage systems, the erosion pattern is more closely related to topography, with most activity on alluvial fans and footslopes (Pickup, 1988). The bare rock and talus slopes of the hill and mountain range country are relatively inaccessible to grazing animals, so runoff and erosion patterns are dominated by topographic effects and are not greatly intensified by grazing. Plant cover might therefore respond in a similar way.

*Topographic effects on moisture availability and runoff*

Topography affects the amount of plant cover through its effect on moisture availability via runoff and runon. Thus, some areas may shed surplus water quickly as runoff or as throughflow in the saturated zone of the soils, so plant-available moisture is relatively low. Other areas gain water by runoff or percolation from upslope and, if slope is limited, may not shed it quickly. These parts of a drainage basin will have higher plant-available moisture levels resulting in more herbage and, frequently, more tree and woody shrub cover.

If a simple overland flow model of runoff is used, the amount of runoff from upslope is a function of the rainfall and the drainage area. Indeed, drainage area, $A$, often may be substituted for water discharge since $Q \propto A^b$, where $b$ is usually in the range 0·1–1·0 (0·6 is a suitable value in central Australia (MacQueen, 1978). Runoff in central Australia also can be greater where terrain is steeper and when the drainage basin is bare (MacQueen, 1978). The opportunity for water to infiltrate during the very short runoff period after a storm partly depends on the time taken to cross a particular slope segment. This depends on flow velocities and, therefore, local slope and roughness.

The key topographic parameters affecting runoff are, therefore, drainage area, $A$, local slope, $S$, and average slope in the drainage basin upstream of a given location, $\bar{S}$. The main vegetation parameter affecting runoff is the amount of bare ground which can be expressed as the area upstream of a point which is unvegetated, $A_b$, or as a percentage, $P_b$.

The overland flow model is probably most appropriate for the plains and bare rock areas of the central Australian mountain ranges. The saturation throughflow model of runoff is an alternative to the overland flow model and may give a better description of processes on the talus slopes of the mountain ranges. In the approach to modelling taken by Beven and Kirkby (1979), a quasi-steady subsurface throughflow system is assumed, in which saturated throughflow across a unit of contour length is approximately equal to recharge to the saturated zone in the upstream contributing area. They propose the following criteria for saturation (and subsequent surface flow) at any point in a drainage basin:

$$\ln(A/S) > s_T/m - s_3/m + \lambda \tag{1}$$

where $A$ is contributing area, $S$ is slope, $s_T$ is the local maximum soil water storage expressed as depth, $s_3$ is the mean subsurface storage in the contributing area, and $m$ and $\lambda$ are catchment constants.

The topographic index $\ln(A/S)$ can be used as an approximate indicator of the distribution of soil water and the potential location of saturation zones in a basin subject to the limitations imposed by assuming uniform soil transmissivity (Jones, 1987). If so, it might also be a determinant of the amount of plant growth in steeper areas (e.g. Band *et al.*, 1993). Moore *et al.* (1988) have also used $\ln(A/S)$ together with the product of $A$ and $S$ to predict erosion intensity and resultant ephemeral gully locations.

*Topographic effects on erosion*

Erosion processes at the regional scale are highly unsteady, spatially variable and involve complex feedbacks which locally damp or enhance behaviour. This situation is normally modelled using steady-state approximations and spatially averaged processes and parameters. Over the long term, the errors involved in these approximations may average out and produce reasonable results (e.g. the hillslope models of Kirkby (1971) and Ahnert (1976)).

Erosion/deposition models vary from complex procedures, in which the equations for water flow on hillslopes are combined with sediment transport equations (Lane *et al.*, 1988), to much simpler procedures based on topographic characteristics and the continuity equation for sediment transport (e.g. Kirkby, 1971; Smith and Bretherton, 1972). In this paper we follow the approach of Kirkby (1987), in which generalized sediment transport relationships are combined with the continuity equation for sediment and applied to topographic data to generate the basic pattern of erosion and deposition.

The continuity equation for sediment transport on a two-dimensional hillslope may be written as:

$$\frac{\partial z}{\partial t} = \frac{\partial s}{\partial x} - \frac{s}{\rho} \tag{2}$$

where $z$ is elevation, $t$ is time, $s$ is the volumetric sediment transport rate, $1/\rho$ is the radius of curvature of the

contours (equivalent to landscape curvature in the direction perpendicular to the line of greatest slope), and $x$ is horizontal distance measured in the direction of greatest slope.

The sediment transport relationship varies with the process involved, but where erosion by runoff dominates, its general form is:

$$s = kQ^m s^n \tag{3}$$

where $Q$ is water discharge, $S$ is slope in the steepest downhill direction (equivalent to $\partial z/\partial x$), and $k$, $m$ and $n$ are empirical coefficients and exponents. Substituting Equation 3 into 2 gives:

$$\frac{\partial z}{\partial t} = k\frac{\partial(Q^m)}{\partial x}s^n + kQ^m\frac{\partial(s^n)}{\partial x} - \frac{kQ^m}{\rho}s^n \tag{4}$$

Values for $m$ frequently lie between 1 and 2 (e.g. Kirkby, 1985; Moore and Burch, 1986). If we use a value of 1 for $m$ and substitute $A^{0\cdot6}$ for discharge, then the key terrain parameters affecting erosion rate are a flow concentration or dispersion term, $\partial A^{0\cdot6}/\partial x$, slope, $\partial z/\partial x$, curvature in the direction of steepest downhill slope, $\partial^2 z/\partial x^2$, radius of contour curvature, $1/\rho$, and $A$, $A_b$ or $\ln(A/S)$ as a substitute for discharge.

## DATA AND METHODS

### *Vegetation cover from remote sensing*

Satellite-based remote sensing is the only practical way of monitoring vegetation pulses at the spatial scale and temporal frequency necessary in arid and semi-arid rangelands. While data from a number of sensors and satellites are available, the Landsat Multispectral Scanner (MSS) is the only one to offer low-cost data and an archive of stored information extending back into the 1970s. This makes it possible to analyse the spatial patterns which have occurred during a number of major vegetation pulses. More recent satellites and sensors, such as SPOT HRV and the Landsat Thematic Mapper, offer better spectral and higher spatial resolution but currently lack a long-term data archive, which limits their usefulness.

Landsat MSS provides coverage of Australia at 16 day intervals in four spectral bands with a spatial resolution or pixel size of 57 m by 79 m. The spectral bands cover the visible green (0·5–0·6 $\mu$m), visible red (0·6–0·7 $\mu$m) and near infrared (0·7–0·8 and 0·8–1·1 $\mu$m) regions of the spectrum. Standardizing MSS data for comparison over time is sometimes a complex procedure but it can be done with reasonable success (e.g. Robinove, 1982; Markham and Barker, 1987; Pickup *et al.*, 1993). It is then possible to calculate a set of vegetation indices from the spectral values in different bands which are closely correlated with the amount of vegetation cover present and its greenness.

Many of the vegetation indices currently in use were developed for application in croplands. Some can also be applied to the estimation of cover in rangelands and many studies have been carried out to test their validity (e.g. McDaniel and Haas, 1982; Graetz and Gentle, 1982). Radiometric studies carried out from aircraft suggest that the better vegetation indices are good surrogate measures of cover and, at the scale of a Landsat pixel, have correlations in the range 0·8–0·9 with cover values determined using ground-based methods (e.g. Foran and Pickup, 1984). Vegetation indices do, however, vary with soil colour (e.g. Huete *et al.*, 1984) and the greenness of the vegetation, which reduces their accuracy for cover estimation.

In this paper, vegetation cover has been estimated using the PD54 index of Pickup *et al.* (1993) and by averaging data from 14 Landsat MSS scenes of central Australia acquired between 1982 and 1989. The PD54 index is calculated by identifying the position of a soil line in the visible red–visible green spectral space. It is also possible to identify locations in the same spectral space normal to this line, representing 100 per cent vegetation cover. Observations lying between these locations and the soil line suggest mixtures of soil and vegetation, with the relative proportion of each depending on distance from the soil line. Other cover indices, such as MSS Band 2 (Graetz *et al.*, 1988) or the normalized difference vegetation index (Band 2 – Band 1/ Band 2 + Band 1), could also be used, but PD54 does seem to produce a better estimate of cover in arid rangelands (Pickup *et al.*, 1993).

PD54 is not suitable for use on sloping terrain without correction for differences in brightness due to

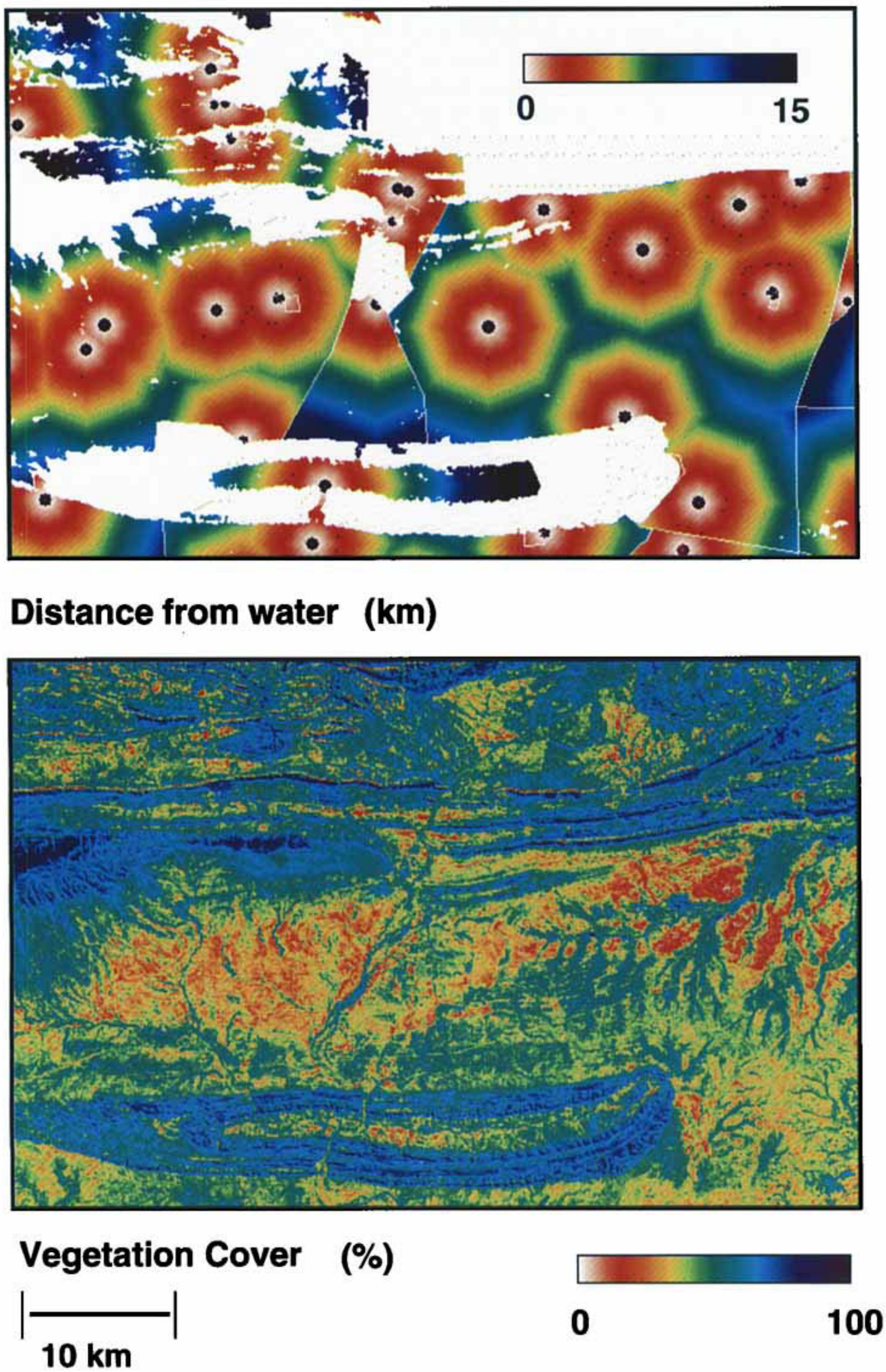


**Plate 1: Distance from water (a surrogate for grazing intensity) and average vegetation cover in the study area. Analyses were carried out both with and without the hill country**

illumination geometry. We have therefore corrected the Band 1 and Band 2 data using the algorithm of Whiteman and Allwine (1986) to determine extraterrestrial solar radiation on inclined surfaces. The correction procedure involves calculating a mean and standard deviation for the Band 1 and Band 2 values for different classes of incident radiation over a large test area. These statistics are then used to rescale the Band 1 and Band 2 values to a reference irradiation level before calculating PD54.

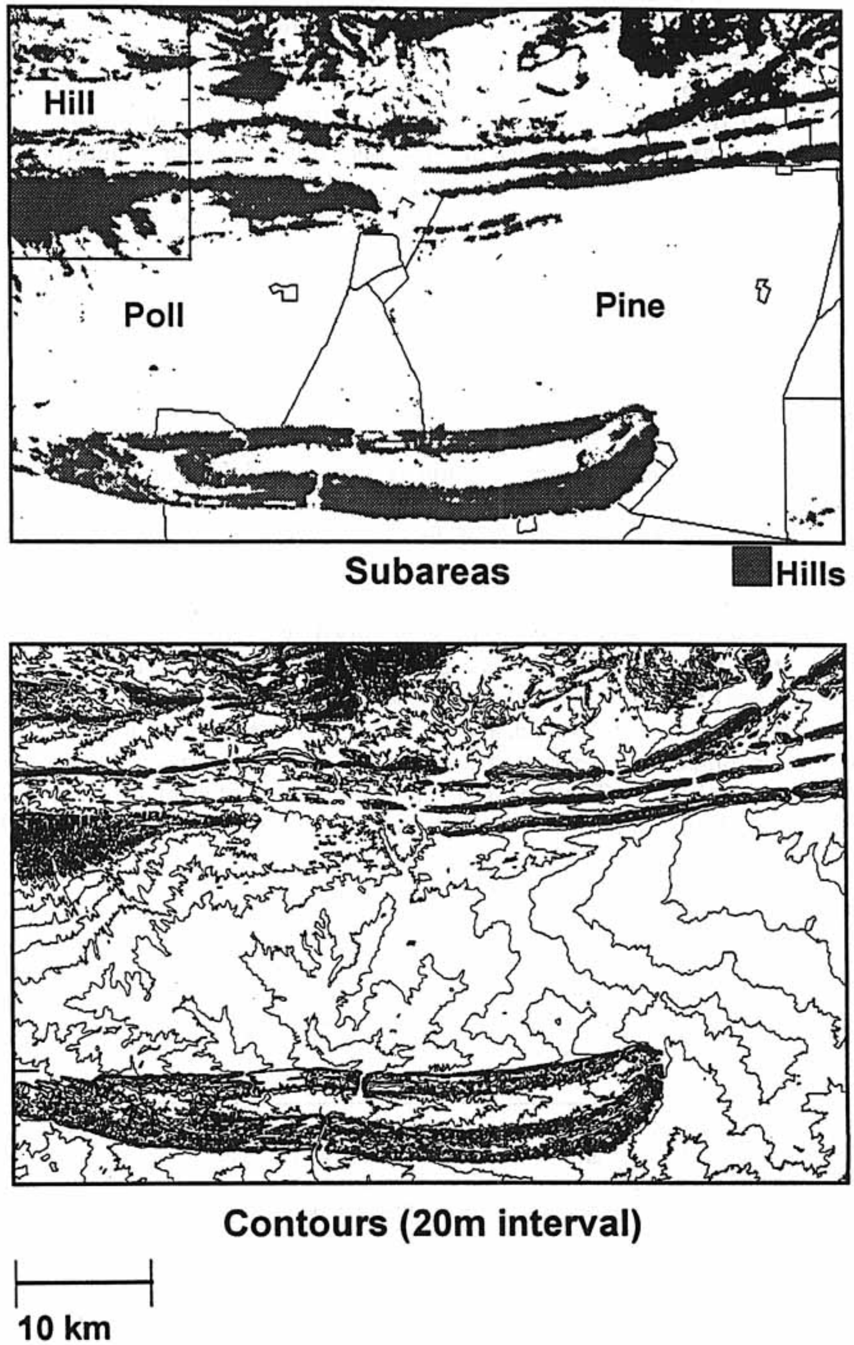


Figure 1. Subareas and topographic data used in the study. The hills are assumed to be ungrazed

*Topographic data*

Topographic data used in this study were derived from a 'hydrologically sound' digital elevation model (DEM) originally obtained from spot heights and 20 m contours mapped at 1 : 100 000 scale. The model has a 100 m grid cell resolution and was derived using Hutchinson's (1988, 1989) techniques. Hydrological accuracy was maintained by forcing topographic lows to occur along mapped streamlines (see Tier and Chewings (1992) for a detailed description of procedures adopted). Most terrain parameters for erosion modelling were determined from the DEM using Braunschweig University's Digital Relief Model (DRM) software (Bork and Rohdenburg, 1986; Bauer, 1988) and include local slope, average slope upstream, area drained, and horizontal and vertical curvature. We also developed routines to calculate the flow concentration/dispersion term, $\partial A^{0\cdot6}/\partial x$.

The amount of runoff from an area is strongly influenced by the amount of bare ground present, for vegetation cover increases interception and detention storage and the amount of infiltration. We have therefore added two parameters which are composites of topography and the amount of vegetation cover present. These are $A_b$, which is the area of bare ground upslope of a given grid cell, and $P_b$, which is the bare area expressed as a percentage of the total. $A_b$ is calculated in the same way as $A$ in the DRM software, but the area of each grid cell is weighted by the percentage bare ground present (determined from the PD54 index) before accumulating along flow lines. $P_b$ is determined as $A_b/A$.

## RESULTS

Topographic and vegetation cover data at 100 m grid cell resolution were derived for a 1000 km$^2$ area close to Alice Springs which has experienced severe erosion (Figure 1 and Plate 1). The area consists of steep mountain ranges with bare rock or talus slopes rising from alluvial fans and lightly dissected footslopes which occupy most of the area. The talus slopes of the mountain ranges are extensively weathered, but there is little in the way of fine-grained soil on the surface. Both ridgetops and slopes are occupied by spinifex (*Triodia clelandii*), but also have a sparse cover of trees and woody shrubs. The fans and footslopes have easily eroded calcareous soils and were probably partly mantled by a veneer of aeolian sand of variable thickness before the introduction of commercial grazing and the arrival of the rabbit in the nineteenth century. The main vegetation types are open woodland or grassland with a sparse tree and woody shrub cover except in the major depositional areas, where tree density can be much greater and canopy cover can be as high as 70 per cent. The mountain ranges and associated talus slopes do not experience significant grazing and are relatively stable in erosional terms. The fans and footslopes are affected by erosion and, since European settlement, have lost much of the sand veneer and underlying material, but with resultant deposition in lower-lying parts of the system.

Table I. Characteristics of subareas used in the analysis

| Subarea | Characteristics | Area (km$^2$) | Mean slope |
|---|---|---|---|
| Pine Paddock | Flat area with fine calcareous soils or clays and sands in sinks. Extensively eroded and strong grazing effects. Hill country excluded. | 515·6 | 0·008 |
| Poll Paddock | Gently sloping alluvial fans with both coarse and fine material. Flatter calcareous areas and sinks similar to Pine Paddock. Extensive erosion and grazing effects. | 300·9 | 0·011 |
| Hill | Steep rocky or talus-covered strike ridges and slopes. Little grazing. Valley floors with finer sediments and grazing effects excluded. | 192·0 | 0·099 |
| Hill + Footslope | Includes the hill subarea, together with the valley floors and the steeper alluvial fans of Poll Paddock. Grazing effects present in the flatter areas but limited in the steeper areas. | 476·1 | 0·068 |

Given the different characteristics of and processes operating on the mountain ranges and on the fans and footslopes, they have been analysed both separately and together as a set of subareas. The subareas are based on individual cattle paddocks because grazing impact varies from one to another depending on stocking history (see Pickup and Chewings, 1994). Individual subareas may include or exclude certain landscape types and so are made up of entirely hill country, hill country plus fans and footslopes, or fans and footslopes only. This makes it possible to examine various combinations of grazed and ungrazed country as listed in Table I and shown in Figure 1.

Initially, attempts were made to use vegetation cover as an erosion/deposition surrogate and to predict its distribution in the study area using Equation 4. This was done by adding a scaling factor to the equation, to permit conversion from calculated erosion or deposition to vegetation cover, and trying to fit the model to cover using a non-linear programming algorithm. The results were poor and yielded correlation coefficients of less than 0·25 for the various subareas and combinations of types of country. Given this lack of success, a more empirical approach was tried by searching for correlations between cover and other variables. This made it possible to introduce the effects of grazing by using distance from water as a surrogate (e.g. Pickup and Chewings, 1988a), and to add biological variables likely to affect runoff and erosion such as the area of bare ground and the percentage bare ground upslope. This methodology is not physically based but it does serve to show what variables and processes have to be considered if erosion modelling is to be developed into an operational tool on vegetated arid zone systems.

Table II lists the correlations between vegetation cover and the various topographic, grazing and upslope vegetation cover parameters described above for each of the subareas. Virtually all the associations are weak except for the linkage between cover and $P_b$, which is discussed later. Log transformation makes little difference to the results except in the case of catchment area and area of bare ground, but this can be expected given that $Q \propto A^b$.

Some of the lack of association between satellite-derived vegetation cover and the other variables arises because of scatter about the relationship between the PD54 vegetation index and observed vegetation cover (Pickup *et al.*, 1993). Other problems arise because cover itself is an imperfect indicator of erosion and deposition (e.g. Pickup and Nelson, 1984). We are therefore looking for general trends rather than close associations with cover.

Inspection of the full correlation matrix indicates that many of the topographic variables are related and may be surrogates for each other. We have therefore divided the topographic variables into groups such that each group represents one of the physical effects contained in Equation 4. So, for example, ln $(A)$, ln $(A_b)$ and

Table II. Correlations between cover and topographic and biological variables for subareas

| | Subarea | | | |
|---|---|---|---|---|
| Variable | Pine | Poll | Hill | Hill + Footslope |
| $\ln(A)$ | 0·118 | 0·052 | −0·027 | −0·107 |
| $\ln(A_b)$ | 0·063 | −0·010 | −0·111 | −0·204 |
| $\ln(A/S)$ | 0·054 | −0·046 | −0·056 | 0·093 |
| $\ln(\underline{S})$ | 0·092 | 0·332 | 0·025 | 0·169 |
| $\partial A^{0.6}/\partial x$ | 0·038 | 0·015 | 0·008 | −0·017 |
| $\partial^2 z/\partial x^2$ | 0·068 | 0·070 | 0·019 | 0·072 |
| $1/\rho$ | 0·096 | 0·065 | 0·054 | 0·037 |
| $D$ | 0·155 | 0·364 | * | * |
| $P_b$ | −0·519 | −0·649 | −0·595 | −0·680 |
| $n$ | 51 560 | 30 092 | 19 204 | 47 606 |

Most values are significant given the large $n$ values
* Variable not appropriate for this subarea

$\ln(A/S)$ can all represent discharge but only one can be used in subsequent correlation and regression-based investigations. This approach may be non-standard in statistical terms but it is logical conceptually. The groups of variables are discussed in turn.

Correlations between cover and the three runoff surrogates, $\ln(A)$, $\ln(A_b)$ and $\ln(A/S)$ are generally low. They are also inconsistent, with both positive and negative values appearing for the same variable in different subareas. The inconsistencies reflect real differences rather than artefacts of the data, and may be the result of differences in slope and the effects of grazing. In the case of $\ln(A)$, increasing drainage area in the steeper country results in greater erosion and less vegetation cover as discharge increases downslope and finer-grained surface materials are encountered. There may also be less throughflow and more runoff on the surface as soil transmissivity is reduced by the downslope reduction in soil grain size. On the fans and footslopes, increased drainage area means increased runoff, but because slopes are low there is more opportunity for infiltration, for deposition of soil and nutrients, and for plant growth. Grazing intensifies this process by increasing runoff from gentle slopes and interfluves and by selective removal of the more palatable plants. The result is a landscape polarized into areas of erosion and intense deposition, with the deposition areas protected by a population explosion of unpalatable plants (Pickup, 1985; 1988). A similar but stronger pattern is seen in the correlations between cover and area of bare ground upslope. This may be because the bare area is a better predictor of runoff than raw drainage area. No obvious slope- or area-related trend can be seen in correlations between cover and $\ln(A/S)$. This is probably because soil transmissivity is not included in this simple topographic index due to lack of data. It may also be due to a change in process from saturation throughflow on the talus-mantled hillslopes to one of Hortonian overland flow on the fans and footslopes.

Correlations between the two slope variables, $\ln(S)$ and $\ln(\bar{S})$, and cover are all positive and are highest in the Poll Paddock and in the Hill + Footslope area, both of which partly overlap. This indicates greater cover on the steeper areas and is probably a grazing effect, since the rocky hill country is relatively inaccessible to cattle and not favoured by rabbits. The low correlations in Pine Paddock may occur because virtually the whole area is subject to grazing or because cover is insensitive to slope at low slope values. They could also arise even if there is a relationship between slope and cover, because the gentler slope values contain more artefacts of the DEM fitting process and resultant errors than the steeper ones. This occurs because the DEM and resultant slopes were calculated using contour data and contours are sparse in relatively flat areas.

Erosion and deposition commonly occur at points in the landscape where topography changes along flow lines and affects sediment transport rates. Several variables represent topographic change in Equation 4, and each has a different effect. Vertical and horizontal curvature, $\partial^2 z/\partial x^2$ and $1/\rho$, describe areas of changing stream power and of potential flow and sediment accumulation or dispersion, and are widely used in models of hillslope evolution. The flow accumulation term, $\partial A^{0 \cdot 6}/\partial x$, is a measure of actual flow accumulation or dispersion and incorporates the effects of upstream contributing area rather than local terrain curvature. While each of these variables is potentially important, their correlations with cover are consistently low, even in hill areas relatively free from grazing and where there is enough contour data to minimize DEM artefacts. The flow accumulation term is the variable least correlated with cover and remains so, even after the removal of other effects by the use of partial correlations. It has therefore been dropped from subsequent investigations. Horizontal and vertical curvature have been retained so that topographic shape effects continue to be represented.

Two variables in Table I represent biological processes: distance from water, $D$, and the percentage of bare area upslope of a point, $P_b$. Distance from water is a good surrogate for grazing intensity (Pickup and Chewings, 1988a) and its effects on cover in the study area have been investigated elsewhere (Pickup and Chewings, 1994). Those investigations confirm the results in Table I and show that there is a weak relationship between cover and distance from water. They also show that simple correlations hide the tendency for cover to decrease under grazing on interfluves, plains and gentle slopes but to increase in hollows. This occurs because grazing generally removes cover but the increased runoff and supply of soil, seed and nutrients from eroded areas encourages deposition and enhanced plant growth along shallow washes and creek lines.

The complex relationship between grazing intensity and cover suggests that another variable is needed to express the impact of loss or gain of cover on downstream processes. The basis for using $P_b$ to represent this effect is the assumption that the amount of cover at a location is a function of rainfall and a balance between enhanced plant growth due to the additional moisture contributed by upslope runoff, and reduced plant growth due to erosion caused by that runoff. If that balance is disturbed by loss of cover upslope due to grazing or some other process, the magnitude of the disturbance is more likely to be a function of the relative change in cover rather than the absolute change. This assumption is vindicated by the high correlations between cover and $P_b$ in Table I compared with the much lower values for the cover–drainage area associations. The effect of $P_b$ on cover is a negative one indicating that, as the proportion of bare ground upslope increases, downstream cover decreases. More upslope runoff therefore translates into more downslope erosion.

To select which variable to use from each group in a consolidated model of the relationship with cover, we have carried out stepwise regressions using the partial correlation of cover with those variables outside the regression model at each stage to determine what should be included. In virtually every case, the same set of variables emerges. We have therefore used a standard model in which the strength of the relationship between cover and each independent variable is expressed as a standardized regression coefficient or $\beta$ value (Ezekiel and Fox, 1959). These coefficients are directly comparable since they are derived from standardized variables.

Model coefficients are listed in Table III. They show that the relationship with cover is dominated by proportion of bare ground upslope in both grazed and ungrazed areas. The next most important effect is distance from water in the grazed areas, followed by slope. The relative influence of slope seems to increase as the subarea becomes steeper or perhaps as the range of slope values increases. The influence of horizontal curvature is limited, but suggests that cover increases in areas of flow accumulation. The influence of vertical curvature is minimal.

The correlation and regression studies on different subareas suggest that some effects on cover may vary downstream or with slope. It is also known from other studies that the erosion or deposition processes associated with local topographic variations, such as terrain curvature, may vary with the absolute value of slope or with discharge (e.g. Montgomery and Dietrich, 1992). Given that slopes generally decrease as drainage area becomes greater, we have sought evidence of changes in processes downslope by fitting the standard model to progressively larger drainage areas within each subarea. This is done by excluding from the analysis all data points whose drainage area is less than a progressively increasing threshold value. Relative changes in the importance of each effect should then appear through changes in the value of the standardized regression coefficients (Figure 2).

The most stable of the regression coefficients are those describing the relationships between cover and vertical curvature and slope. These relationships are also relatively weak, although they remain significantly

Table III. Results of multiple regression analysis between cover and selected topographic and biological process surrogate variables

| Variable Standardized regression coefficient | Subarea | | | |
|---|---|---|---|---|
| | Pine | Poll | Hill | Hill + Footslope |
| $P_b$ | −0·549 | −0·608 | −0·600 | −0·644 |
| $D$ | 0·106 | 0·159 | | |
| $\ln(A_b)$ | 0·128 | −0·110 | 0·022 | −0·057 |
| $\ln(S)$ | −0·073 | 0·034 | 0·070 | 0·138 |
| $\partial^2 z/\partial x^2$ | −0·027 | 0·005 | −0·004 | 0·041 |
| $1/\rho$ | 0·013 | 0·078 | 0·051 | 0·055 |
| $R^*$ | 0·550 | 0·685 | 0·601 | 0·702 |

* $R$ is the multiple correlation coefficient

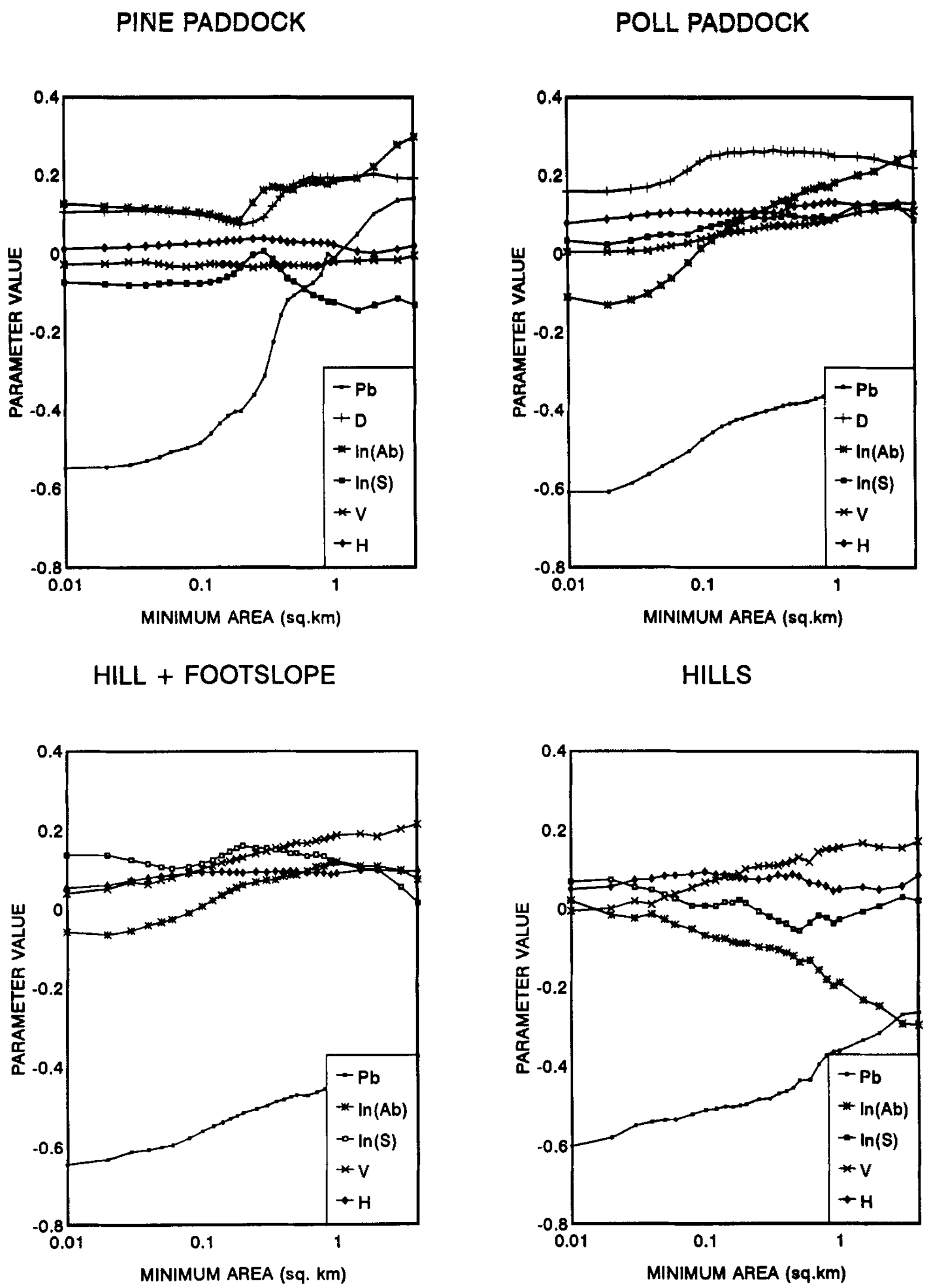


Figure 2. Standardized regression coefficients for the relationship between cover and other variables in progressively larger drainage areas. The term $V$ in the key denotes vertical curvature, $\partial^2 z/\partial x^2$, while $H$ denotes horizontal curvature, $1/\rho$

different from zero over most of the range. The others are more dynamic, with the greatest changes occurring in the coefficients for $P_b$, which is the strongest predictor of cover. Here, the values become progressively smaller for larger areas and, in Pine Paddock, eventually change from negative to positive. This reflects a shift in process from one where an increase in the percentage of bare ground produces more runoff, with

resultant erosion and less cover downslope, to another in which infiltration from the additional runon enhances plant growth in the less steep areas of larger drainage basins.

Changes in the coefficient for ln ($A_b$), which represents the area of bare ground rather than the proportion of it, are rather different. In the hills, the bare area upslope has an increasingly strong inverse relationship with cover for larger drainage areas. This presumably reflects increased runoff and increased downslope erosion. When hills and footslopes are combined, the effect is much weaker and varies from weakly inverse to weakly direct as progressively smaller catchment areas are excluded. In the Pine and Poll Paddocks there is more systematic variation, and coefficient values are positive over much of the range and increase with drainage. These differences reflect the processes referred to previously. In the steep hill country, more bare ground means more runoff and erosion downslope and therefore less vegetation cover. In the flatter areas, more runoff upslope means more runoff into sinks, with more infiltration, more deposition and more plant growth.

The coefficients describing the effect of vertical curvature on cover have values close to zero and remain fairly constant in the relatively flat Pine Paddock. This is to be expected given the level of error in slopes and the presence of DEM artefacts in areas where contours are sparse. The other subareas have steeper country and here the effect of increasing vertical curvature is to produce more vegetation cover. This effect also increases in importance as drainage basins become larger. Positive values of vertical curvature indicate concave-upward slopes where decreasing gradient in the downslope direction promotes deposition and more vegetation cover. Convex slopes are more frequently associated with downslope erosion in continuity-based models (e.g. Armstrong, 1987), so convexity should be associated with reduced cover as indicated by the regression coefficients.

The pattern of change in the coefficient describing the effect of distance from water on cover in both the Pine and Poll Paddocks shows that it is a better predictor of cover as drainage area becomes larger. The improvement seems to occur as a step change when areas smaller than 0·1–0·3 $km^2$ are excluded from the analysis. This may occur because a large part of both subareas has been grazed so heavily that the smallest catchments relatively close to water are virtually bare for much of the time. It is only when the upstream area is large enough to provide sufficient runoff to allow additional infiltration and extra plant growth that the distance-from-water effect in grazing begins to appear (see Pickup and Chewings (1994) for a more detailed study of grazing impacts on cover in this area). The threshold effect may also result from the presence of a larger number of trees and woody shrubs in areas with more runon from upslope. This means greater residual cover during drought, when the herbage virtually disappears.

## IMPLICATIONS

If vegetation cover is a reasonable surrogate indicator of erosion and deposition, then it is clear that contemporary patterns of geomorphic activity in the arid rangelands of central Australia are dominated by biological processes rather than the effects of terrain. The most effective predictor of downslope vegetation cover is the percentage of bare ground upslope in the smaller catchments. This explains why simple, physically based erosion models that use topographic characteristics but lack a biological component are unlikely to be successful in explaining observed patterns of vegetation cover. Terrain effects become more important and the impact of upstream cover diminishes in larger drainage basins, but upstream cover is still the most important predictor over most of the area.

Few distributed erosion models have the capacity to incorporate the effects of vegetation, although progress is being made (e.g. Kirkby and Neale, 1987; Lane and Nearing, 1989). There is also the difficulty and high cost of producing DEMs with sufficient accuracy to allow distributed modelling, especially in flatter areas. Under these circumstances, the approach to operational modelling and forecasting of erosion risk developed by the authors (e.g. Pickup and Chewings, 1988b) is still the only practical technique in Australian rangelands. In this approach, vegetation cover, as detected from remotely sensed data, is used as an erosion surrogate, and stochastic pattern modelling techniques are used to transfer the spatial characteristics of eroded landscapes to less eroded situations. This may be less satisfying theoretically but at least it allows for biological effects, such as the impact of plant cover and grazing, to be incorporated into the prediction of erosion risk.

## REFERENCES


Ahnert, F. 1976. 'Brief description of a comprehensive three-dimensional process-response model of landform development', *Zeitschrift für Geomorphologie Supp. Bd.*, **25,** 29–49.

Armstrong, A. C. 1987. 'Slopes, boundary conditions, and the development of convexo-concave forms—some numerical experiments', *Earth Surface Processes and Landforms*, **12,** 17–30.

Band, L. E., Pittman, P., Nemani, R. and Running, S. W. 1993, 'Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology', *Agricultural and Forest Meteorology*, **63,** 93–126.

Bauer, J. 1988. *User's guide to the Digital Relief Model*, Department of Physical Geography and Landscape Ecology, Technical University Braunschweig, Langer Kamp 19c, D3300 Braunschweig, West Germany.

Beven, M. J. and Kirkby, M. J. 1979. 'A physically-based, variable contributing area model of basin hydrology', *Hydrological Sciences Bulletin*, **24,** 43–69.

Biot, Y. 1993. 'How long can high stocking densities be sustained?', in Behnke, R. H., Scoones, I. and Kerven, C. (Eds), *Range Ecology at Disequilibrium*, Overseas Development Institute and International Institute for Environment and Development, London, 153–172.

Bork, H. R. and Rohdenburg, H. 1986. 'Transferable parameterization methods for distributed hydrological and agroecological catchment models', *Catena*, **13,** 99–117.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R. and McKean, J. 1993. 'Analyses of erosion thresholds, channel networks and landscape morphology using a digital terrain model', *Journal of Geology*, **101,** 259–278.

Eldridge, D. J. and Rothon, J. 1992. 'Runoff and sediment yield from a semi-arid woodland in eastern Australia. 1. The effect of pasture type', *The Rangeland Journal*, **14,** 26–39.

Ezekiel, M. and Fox, K. A. 1959. *Methods of Correlation and Regression Analysis: Linear and Curvilinear*, John Wiley, New York.

Foran, B. D. and Pickup, G. 'Relationships of aircraft radiometric measurements to bare ground on semi-desert landscapes in central Australia', *Australian Rangeland Journal*, **6,** 59–68.

Frank, T. D. 1984. 'The effect of change in vegetation cover and erosion patterns on albedo and texture of Landsat images in a semi-arid environment', *Annals of the Association of American Geographers*, **74,** 393–407.

Friedel, M. H. 1984. 'Biomass and nutrient changes in the herbaceous layer of two central Australian mulga shrublands after unusually high rainfall', *Australian Journal of Ecology*, **9,** 27–38.

Friedel, M. H., Pickup, G. and Nelson, D. J. 1993. 'The interpretation of vegetation change in a spatially and temporally diverse arid Australian landscape', *Journal of Arid Environments*, **24,** 241–260.

Graetz, R. D. and Gentle, M. R. 1982. 'The relationships between reflectance in the Landsat wavebands and the composition of an Australian semi-arid shrub rangeland', *Photogrammetric Engineering and Remote Sensing*, **48,** 1721–1730.

Graetz, R. D., Pech, R. P., Gentle, M. R. and O'Callaghan, J. F. 1986. 'The application of Landsat image data to rangeland assessment and monitoring: the development and demonstration of a land image-based resource information system', *Journal of Arid Environments*, **10,** 53–80.

Graetz, R. D., Pech, R. P. and Davis, A. W. 1988. 'The assessment and monitoring of sparsely vegetated rangelands using calibrated Landsat data', *International Journal of Remote Sensing*, **9,** 1201–1222.

Hill, J., Smith, M. O., Mehl, W. and Altherr, M. 1993. 'The use of AVIRIS data for land degradation and soil erosion hazard mapping in a Mediterranean ecosystem', Paper presented at the 25th International Symposium on Remote Sensing and Global Environmental Change, Graz, Austria.

Hodder, R. M. and Low, W. A. 1978. 'Grazing distribution of free-ranging cattle at three sites in the Alice Springs District, central Australia', *Australian Rangeland Journal*, **1,** 95–105.

Hoffmann, L., Ries, R. E. and Gilley, J. E. 1983. 'Relationships of runoff and soil loss to ground cover on native and reclaimed grazing land', *Agronomy Journal*, **75,** 599–602.

Huete, A. R., Post, D. F. and Jackson, R. D. 1984. 'Soil spectral effects on four space vegetation discrimination', *Remote Sensing of Environment*, **15,** 155–165.

Hutchinson, M. F. 1988. 'Calculation of hydrologically sound digital elevation models', *Procs. Third International Symposium on Spatial Data Handling*, Sydney, Australia, 117–133.

Hutchinson, M. F. 1989. 'A new procedure for gridding elevation and stream line data with automatic removal of spurious pits', *Journal of Hydrology*, **106,** 211–232.

Johns, G. G. 1983. 'Runoff and soil loss in a semi-arid shrub invaded poplar box (*Eucalyptus Populnea*) woodland', *Australian Rangeland Journal*, **5,** 3–12.

Jones, J. A. 1987. 'The initiation of natural drainage networks', *Progress in Physical Geography*, **11,** 205–245.

Kirkby, M. J. 1971. *Hillslope process-response models based on the continuity equation*, Transactions of the Institute of British Geographers Special Publication **3,** 15–30.

Kirkby, M. J. 1985. *A two-dimensional model for slope and stream evolution*, School of Geography Working Paper **419,** University of Leeds.

Kirkby, M. J. 1987. 'Modelling some influences of soil erosion, landslides and valley gradient on drainage density and hollow development', *Catena Suppl.* **10,** 1–14.

Kirkby, M. J. and Neale, R. H. 1987. 'A soil erosion model incorporating seasonal factors', in Gardiner, V. (Ed.), *International Geomorphology 1986 Part II*, John Wiley, Chichester, 189–210.

Lane, L. J. and Nearing, M. A. 1989. *USDA Water Erosion Prediction Project: Hillslope Profile Version*, National Soil Erosion Research Laboratory Report **2,** National Soil Erosion Research Laboratory, U.S. Department of Agriculture Agricultural Research Service.

Lane, L. J., Shirley, E. D. and Singh, V. P. 1988. 'Modelling erosion on hillslopes', in Anderson, M. G. (Ed.), *Modelling Geomorphological Systems*, John Wiley, Chichester, 287–308.

MacQueen, A. D. 1978. *Flood Frequency in Central Australia—a Regional Model*, Water Division, Department of Transport and Works, Northern Territory.

Markham, B. L. and Barker, J. L. 1987. 'Radiometric properties of U.S. processed Landsat MSS data', *Remote Sensing of Environment*, **22,** 39–71.

McDaniel, K. C. and Haas, R. H. 1982. 'Assessing mesquite-grass vegetation condition from Landsat', *Photogrammetric Engineering and Remote Sensing*, **48**, 441–450.

Montgomery, D. R. and Dietrich, W. E. 1992. 'Channel initiation and the problem of landscape scale', *Science*, **255**, 826–830.

Moore, I. D. and Burch, G. J. 1986. 'Modelling erosion and deposition: topographic effects', *Transactions of the American Society of Agricultural Engineers*, **29**, 1624–1630, 1640

Moore, I. D., Burch, G. J. and MacKenzie, D. H. 1988. 'Topographic effects on the distribution of surface soil water and the location of ephemeral gullies', *Transactions of the American Society of Agricultural Engineers*, **31**, 1098–1107.

Moore, I. D., Grayson, R. B. and Ladson, A. R. 1991. 'Digital terrain modelling: a review of hydrological, geomorphological and biological applications', *Hydrological Processes*, **5**, 3–30.

Noy-Meir, I. 1973. 'Desert ecosystems: environment and producers', *Annual Review of Ecology and Systematics*, **4**, 25–51.

O'Loughlin, E. M. 1986. 'Prediction of surface saturation zones in natural catchments by topographic analysis', *Water Resources Research*, **22**, 794–804.

Pickup, G. 1985. 'The erosion cell—a geomorphic approach to landscape classification in range assessment', *Australian Rangeland Journal*, **7**, 114–121.

Pickup, G. 1988. 'Modelling arid zone soil erosion at the regional scale', in Warner, R. F. (Ed.), *Fluvial Geomorphology of Australia*, Academic Press, Sydney, 105–127.

Pickup, G. and Chewings, V. H. 1988a. 'Estimating the distribution of grazing and patterns of cattle movement in a large arid zone paddock: An approach using animal distribution models and Landsat imagery', *International Journal of Remote Sensing*, **9**, 1469–1490.

Pickup, G. and Chewings, V. H. 1988b. 'Forecasting patterns of erosion in arid lands from Landsat MSS data', *International Journal of Remote Sensing*, **9**, 69–84.

Pickup, G. and Chewings, V. H. 1994. 'A grazing gradient approach to land degradation assessment in arid areas from remotely-sensed data', *International Journal of Remote Sensing*, **15**, 597–617.

Pickup, G. and Nelson, D. J. 1984. 'Use of Landsat radiance parameters to distinguish soil erosion, stability and deposition in arid central Australia', *Remote Sensing of Environment*, **16**, 195–209.

Pickup, G., Chewings, V. H. and Nelson, D. J. 1993. 'Estimating changes in vegetation cover over time in arid rangelands using Landsat MSS data', *Remote Sensing of Environment*, **43**, 243–263.

Robinove, C. J. 1982. 'Computation of physical values for Landsat digital data', *Photogrammetric Engineering and Remote Sensing*, **48**, 781–784.

Smith, T. R. and Bretherton, F. P. 1972. 'Stability and the conservation of mass in drainage basin evolution', *Water Resources Research*, **8**, 1506–1529.

Stafford Smith, M. and Pickup, G. 1993. 'Out of Africa, looking in: Understanding vegetation change', in Behnke, R. H., Scoones, I. and Kerven, C. (Eds) *Range Ecology at Disequilibrium*, Overseas Development Institute and International Institute for Environment and Development, London, 196–226.

Thornes, J. B. 1990. 'The interaction of erosional and vegetational dynamics in land degradation: spatial outcomes', in Thornes, J. B. (Ed.), *Vegetation and Erosion*, John Wiley and Sons, Chichester, 41–53.

Tier, G. and Chewings, V. H. 1992. 'The calculation of a useable digital elevation model for habitat modelling in Central Australia', *Procs 6th Australasian Remote Sensing Conference, Wellington, New Zealand*, 3.

Warren, P. L. and Hutchinson, C. F. 1984. 'Indicators of rangeland change and their potential for remote sensing', *Journal of Arid Environments*, **7**, 104–126.

Westoby, M. 1980. 'Elements of a theory of vegetation dynamics in arid rangelands', *Israel Journal of Botany*, **28**, 169–194.

Whiteman, C. D. and Allwine, K. J. 1986. 'Extraterrestrial solar radiation on inclined surfaces', *Environmental Software*, **1**, 164–169.